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Technological review on solar PV in Pakistan: Scope, practices and recommendations for optimized system design

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ABSTRACT

Due to increasing fossil fuel prices and their limited availability, the global energy focus is shifting towards renewable resources. However, the uptake of these resources by Pakistan is rather slow. Various factors such as political interference, social unacceptability and economic barriers are deterring the widespread use of these resources. In addition, there is a consensus in the literature that technological knowledge of solar PV in Pakistan is limited at best. Many studies have indicated technological shortcomings as one of the major barriers in PV growth, however very little or no work has been reported which could actually address these issues. This paper reviews the current state of affairs in solar PV with a focus towards the technological shortcomings. We highlight various inefficient practices in the system design which lead to un-optimized and unreliable systems, thus contributing towards the lack of social acceptability of PV. We also propose several modifications that should be added to the design process of such systems to make them more accurate and reliable. Conforming to proper design methodologies and detailed understanding of technological aspects will go a long way in making PV grow in Pakistan.

Contents

1. Introduction

Due to urbanization and increase in population, the global demand for energy is ever increasing. It is estimated that the global energy demand will increase at the rate of 1.7% per year

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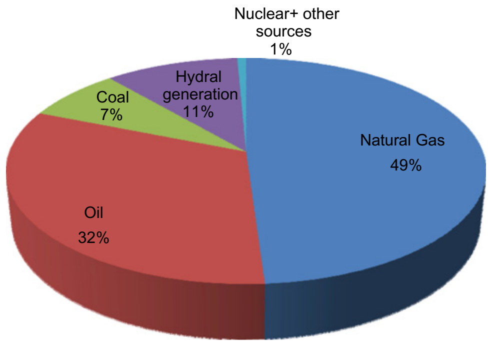

Fig. 1. Energy mix of Pakistan.

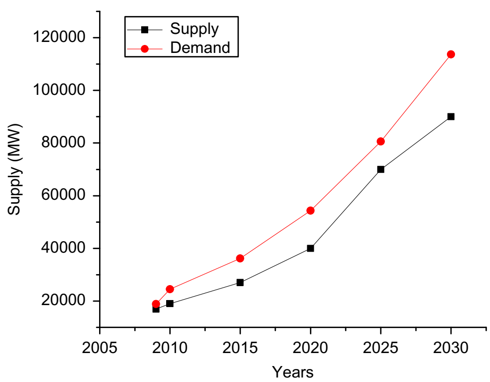

Fig. 2. Peak electricity demand vs. supply projections for Pakistan.

and the demand will reach 16.5 billion tons of oil equivalents (TOE) by 2030 [1]. Trends suggest that fossil fuels will continue to dominate the energy mix in years to come and renewables will slowly increase their share in the energy mix of the planet [2]. Pakistan is heavily reliant on fossil fuels for its primary energy needs and the overall energy mix is shown in Fig. 1 [3]. Pakistan, being a developing country, is dependent on this 'imported energy' as around 60% of the total foreign exchange is spent on the import of fossil fuels. It imports 308.9 thousand barrels per day and the indigenous production is still less than 63,000 barrels per day [4]. Although Pakistan has large reserves of coal in Thar (175 billion tons [5]) and other regions, it still imports 4.7 million short tons compared to 3.8 million short tons of indigenous production adding to its large fuel import bill [6]. In addition, these conventional resources are subject to dynamic price changes which are undesirable and add to economic problems due to the fickle state of the economy. The energy demand of the country has increased by 28% over the last four years and by 2025, it is expected to increase by 85% [7]. This will add to the financial worries of the country and the energy problems are expected to aggravate further in future.

Electricity deficit of the country is increasing every year which is evident from the demand-supply chart in Fig. 2 [8]. It compares the projected peak demand of electricity in the country, by Pakistan Electric Power Company (PEPCO) which is the main power regulating body in Pakistan, with the supply forecast. Apart from fossil fuels, among other energy resources, hydro contributes around 30% to the total electricity production of Pakistan and the current installed capacity of hydro is 6444 MW. The contribution due to wind is 50 MW which has recently been integrated with the national grid. The projected demand-supply deficit in 2030 may have severe implications to the overall economy of the country.

The driving force for Pakistan's economy is electricity and due to the shortage of electricity, the industrial sector has been adversely affected and overall exports of the country have been reduced. The 'load shedding' (unavailability of grid power) in the country is aggravating the situation as these periodic power shutdowns are severely affecting the industrial output and crippling the country's economy. It is estimated that load shedding is costing 2.5 billion $/year to Pakistan's economy which is on an average 2% dent to the country's GDP. In addition, it has also caused a loss of employment to around 400,000 people annually within Pakistan [9]. According to a survey by world bank [10], 66.7% of the businesses in Pakistan identify shortage of electricity as the major business obstacle ahead of corruption and crime/terrorism which are 11.7% and 5.5%, respectively.

Fortunately, Pakistan has a high renewable energy potential which is elaborated in many studies on Pakistan [9–13]. Renewable energy outlook along with solar perspective is discussed by Mirza et al. 2003 [11] and Sheikh 2010 [12]. The institutional set up and its limitation along with some of the broader challenges have been assessed by Sahir et al. 2008 [13] and Bhutto et al. 2012 [14]. Analytic hierarchy process (AHP) has also been used by Amer et al. 2011 [15] for the energy sector in Pakistan and it has shown potential of various renewable sources for electricity generation in the country. Policy constraints have also been highlighted by Khan et al. 2010 [16] in their study of solar energy in the Pakistan scenario.

In all of the above mentioned studies, authors broadly summarize the potential, institutional setups, various social barriers, market related barriers and policy shortcomings. All of these studies also identify technological barriers as one of the prime deterrents for PV growth, yet no detailed account of actual technological shortcomings and basic design flaws have been addressed for the PV sector in Pakistan. Therefore, in this work, we have identified the actual technological barriers which have deterred investors and domestic users to invest in this technology to cater for their needs. We have also identified optimum components and technology which is suitable for energy generation in remote locations within the country. Better planning and reliable component selection will go a long way in minimizing some of the social barriers as well, which restrict the use of PV based on a broad cliché in Pakistan that 'PV just doesn't work'. We believe that it is only due to lack of proper planning that users in Pakistan are generally disconcerted with PV and blame the technology itself for not being good enough.

Globally, PV is a well understood and optimized technology and we see an increasing trend towards the use of this technology as policies are being tailored for its increasing use [17,18]. We believe, with proper selection of technology incorporating all the relevant parameters, PV technologies can emerge as a most common and effective solution for energy crisis in Pakistan. To the best of our knowledge, this study is the first of its kind which evaluates the technological constraints and quantifies the efficiency constraints for PV systems in Pakistan. We also propose best practices which will contribute to the growth of PV generated electricity in the country.

2. Review of renewable energy resources in Pakistan

Pakistan has a high potential for almost all types of renewable energies. These include solar (PV and thermal),wind, biogas, micro-hydal/canal fall, biodiesel production, biomass/waste to energy production, geothermal, tidal/ocean energies, etc. [12]. The resource potential about most of these renewable energies in the country has already been discussed in considerable detail [19–21]. However, two renewable resources in solar and wind are particularly important as they have the highest potential for electricity generation.

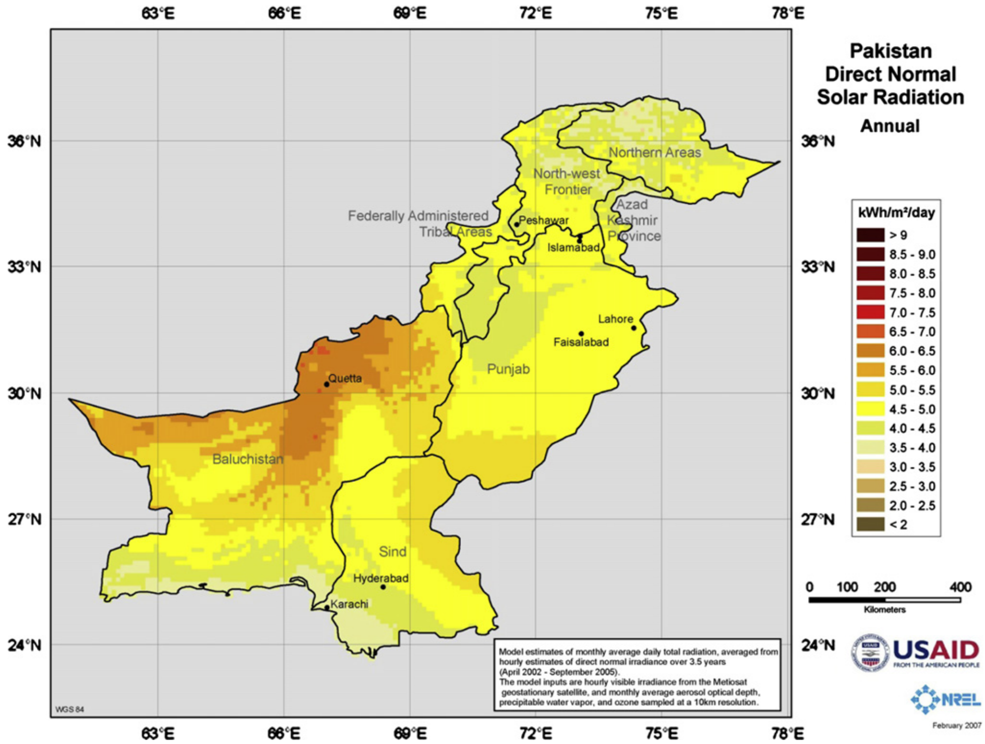

Fig. 3. Solar map of Pakistan developed by NREL and USAID [23].

The overall wind potential is around 346,000 MW [22]. Although this potential is large, the opportunity presents itself only in certain coastal areas of Pakistan. Transmission of this power to other provinces requires transmission network changes which itself is a monumental task for a cash-stripped country like Pakistan. It should also be noted that most of the countries do not have access to the national grid. According to a survey in 2005, almost 32% of Pakistan's 125,000 villages i.e. 40, 000 villages are not grid-connected [12]. So, the use of wind power is limited for remote users and the users connected to unreliable grid.

Pakistan is also blessed with abundant sunlight. The surface insolation levels in most of the cities are among the highest in the world. In most cities, the average daily surface solar energy is above 5 kW/m^2/day. Certain areas in Baluchistan have insolation levels as high as 8.5 peak-sunlight-hours daily [23] with up to 2700 peak-sunlight hours/year [24,25]. The overall solar potential for Pakistan is summarized in Fig. 3 which shows the direct normal solar irradiation for the entire country. It is important to utilize this most readily available natural resource in the form of sunlight for electricity generation which could add significantly to the overall energy mix of the country.

3. Topologies for electricity generation through PV

It is a general perception that electricity generation due to PV is more expensive than the electricity generated through conventional sources. However, in recent years a decreasing trend has been observed for the price of PV technology. The cost of the panels itself has decreased by 60% between 2008 and 2011 to $ 0.7/Wp [26]. The overall system cost of a grid-tied PV system including panels, electronics, parts and labor has decreased to $ 1.67/Wp [26]. This has resulted in an annual growth rate for stand-alone PV and Grid-tied solar PV globally for 2010 to be 72% and 81%, respectively [27]. Due to this decrease in the price, the policy support for solar energy has increased and more than 100 countries have enacted new renewable energy policies.

Due to these decreasing trends in the cost of PV installations, this paper focuses on the state of affairs of PV in Pakistan. Two systems namely grid tied solar and stand-alone solar solutions are identified and the stand-alone solar solution is discussed in detail.

3.1. Grid connected systems

One way of using solar power is through grid-tied solar technology. In this topology, the solar energy from the array is fed directly to the grid. The maintenance required for grid connected solar PV is mostly the cleaning of the panels. Grid-tied inverters usually have smaller life span than solar panels. However, no regulations currently exist on net-metering in Pakistan and therefore there are no benefits for domestic consumers feeding power into the national grid. In addition, most of the countries do not have access to a reliable grid and therefore this topology is only relevant for Independent Power Producers (IPPs) and large businesses and industries which having captive generation. Currently there is only one such system installed in Pakistan which is of 360 KW.

The reliability of national grid is low which manifests in the form of periodic shutdowns. The grid-tied systems cease to operate when grid power is off and limits the use of this topology for large scale distributed generation. There are certain technologies that operate in islanding, in case of a grid shutdown, but are expensive. For this reason, this is currently not a suitable technology in Pakistan for small-scale consumers, cottage industry and remote areas which do not have access to the grid, in the first place.

3.2. Stand-alone backup systems

Second and more relevant topology is off-grid and stand-alone solar power generation. This solution can also be utilized for rural electrification of areas where the national grid is not available. Certain other applications, such as solar water pumps and solar

heaters can also be based on this technology. For example, in Pakistan, agricultural water pumps account for up to 2500 MW of load on national grid [28] which constitutes to 12.5% of the overall power demand in the country. This load and some other applications can be easily shifted to standalone PV generation which could easily reduce the overall demand.

Stand-alone PV can also be used in other parts of the country where regular power outages can be catered with solar PV-based uninterruptable power supplies. In addition, medium enterprises and industrial consumers can opt for reliable PV backups instead of fossil fuel based (diesel) generation for its critical process. This will also lower their carbon footprint and will add to the country's efforts in reducing the greenhouse emissions.

4. Stand-alone system for distributed generation

A basic standalone PV back-up system, for most domestic consumers and cottage industry, is summarized in Fig. 4. It comprises of solar panels/array, charge controllers, battery bank and an inverter to supply energy to electrical loads. A brief discussion of each component is given in this section.

4.1. Solar panels/arrays

Solar cells convert energy from sunlight into electrical energy and are the basic components of any solar PV based system. Many of such cells constitute a solar panel.

When light of appropriate wavelength falls on a semiconductor, the photons transmit their energy to the outermost (valence) electrons of the constituent atoms. For every absorbed photon, an electron is generated which is free to move in the conduction band. When it does so, it leaves behind a vacancy called a hole. It is this generation of electrons and holes that result in a current flowing through a semiconductor. This principle is utilized in the electricity generation from solar cells. The energy of the sunlight reaching earth surface is distributed from 300 nm to 2000 nm and solar cells are optimized to absorb maximum power from the sunlight.

In conventional solar cells (such as crystalline-Si), the electric field is created at the junction between *p*- (doped with Boron) and *n*- (doped with Phosphorous) regions. This field separates the light-generated holes and electrons and produces a current in the external circuit along with a voltage across the cell [29]. The maximum value of the cell voltage occurs in an open circuit mode and the maximum current flows in a short circuit mode [30]. A realistic model of a solar cell encompassing the above mentioned characteristics is shown in Fig. 5.

Eq. (1) links the output voltage and current of the solar cell [31]:

$$I = I_{ph} - I_0(e^{q(V_{out}+IR_s)/nkT}) - \frac{V_{out}+IRs}{R_{sh}} \quad (1)$$

where R_s is the series resistance and R_{sh} is the shunt resistance of the solar cell. I_{ph} and I_o are light-generated and recombination currents, respectively.

The origin of the shunt resistance R_{sh} is due to the leakages around the edges of a cell, diffusion paths along the dislocations and small metallic short circuits. In practice, even in concentrated sunlight conditions, this resistance is considerably large and therefore has a negligible effect. However, the series resistance R_s is critical in the device performance as it is primarily due to the resistance of the metallic contacts along with the resistance of semiconductor bulk (mainly emitter sheet resistance). I_{ph} is modeled by a current source which depends on incident illumination and conversion efficiency. The inherent *p*–*n* junction in the device is modeled by the diode parallel to the photo generated current.

To achieve a practical voltage and current, multiple solar cells are connected and the circuit arrangement depends on the requirement of the system. Individual cells are added in series to achieve a higher output voltage. Similarly, to get a high output current, they are arranged in parallel. Generally, 60–80 cells are arranged in commercially available solar panels. These cells are packaged (encapsulated) for protection and the overall arrangement constitutes a photovoltaic generator which is more commonly known as a solar panel. Fig. 6 shows the normalized output power of a commercially available solar panel against its generated voltage.

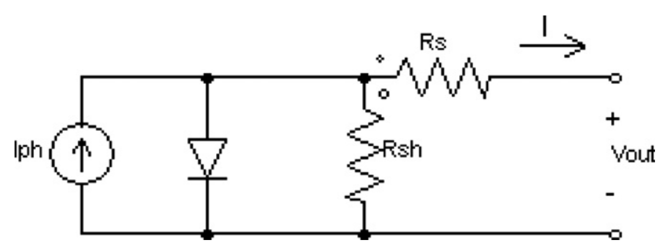

Fig. 5. Equivalent model of solar cell.

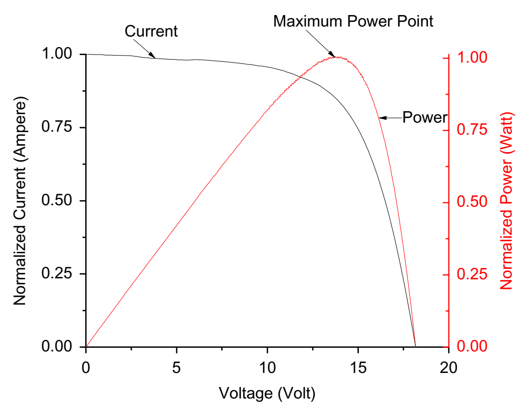

Fig. 6. Solar cell's normalized current and power versus its voltage showing the maximum power point.

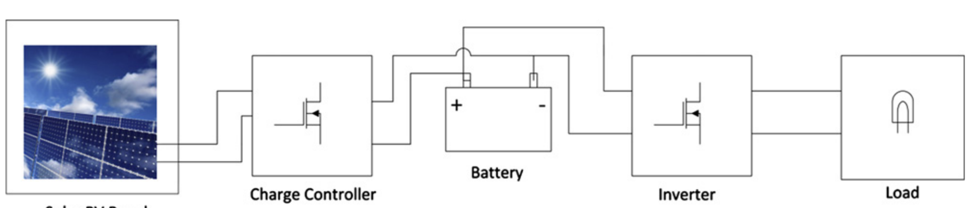

Fig. 4. Overall stand-alone PV system.

Typically, the output power of a solar panel is not constant and it varies with incident radiation. There is a single operating point where output power of the solar panel is maximum, hence the name maximum power point. Therefore, if the panel is operated at this voltage, maximum power can be extracted. It is imperative to extract maximum available power out of a panel or an array since the efficiency of the cells is inherently low. Operating the system on maximum power point lowers the overall size of the PV array and in turn the cost.

Commercially available solar panels can broadly be categorized into two types:

1. Crystalline Silicon (c-Si) based PV generators:
   These panels enclose cells which are based on mono-crystalline and poly-crystalline Si. These are the most predominant panels commercially available throughout the world constituting 80–90% of the overall market [32]. The efficiency of the commercial panels is in the range of 14–20% [33].
2. Thin film based PV generators:
   These panels enclose cells which are based on materials such as amorphous Silicon, Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). The panels based on thin film technology have slightly lower cost since smaller cell widths of the absorbing materials are used. However, the efficiency of these panels is low and typically ranges from 8% to 12% [33].

4.2. Charge controllers

A charge controller is a circuit that is usually used to charge batteries from solar panels. The output of a solar panel varies throughout a day with the change in the intensity of incoming sunlight. Therefore, a charge controller (a dc–dc converter) is required to regulate the battery charging mechanism by usually stepping down the voltage form the panel to a 12-V dc bank. In order to charge high voltage battery banks (24/48 V), a boost type dc–dc converter is used as the battery voltage may be larger than the output voltage of the solar module.

Based on the working, charge controllers can be divided into the following two categories:

- PWM charge controllers
- MPPT charge controllers

PWM (pulse width modulated) charge controllers have a basic purpose of charging the battery and preventing it from overcharging which could lower the life of a battery. In addition, these controllers cease the operation at low battery voltage conditions. The output power from the panels is dictated by the charging requirements of the battery.

MPPT charge controllers are more sophisticated as they operate the solar panels at their maximum power point in addition to the basic function of PWM controllers. MPPT based chargers are more expensive, however they can increase the overall power output from a panel by 30% [34]. These controllers continuously track the maximum power point (MPP) such that a new value of MPP is achieved if irradiance or ambient conditions change.

A typical buck-boost converter is shown in Fig. 7.

The output voltage of the above converter can be controlled as described by Eq. (2) [35]:

$$V_{out} = V_{in} \times \frac{D}{D-1} \tag{2}$$

where, D is the duty cycle of the square waveform operating the switch S1. By the variation of D, we can control output current in accordance with the requirements of the battery bank as the output voltage is dictated by the battery bank. Therefore, using the parameter D, we can also operate the solar panel at its maximum power point.

4.3. Battery bank

Battery bank consists of series and/or parallel combination of batteries to get a desired output voltage and current rating. There are different types of batteries available that can be used. However, lead-acid based batteries are primarily used for PV applications due to their low cost. Common types of these batteries are:

- Flooded lead acid battery
- Absorbent glass mat (AGM) lead-acid battery
- Gel-based lead-acid battery

Flooded batteries are not designed for deep discharges and require periodic maintenance and are most unsuitable for PV systems. AGM and Gel batteries both are deep discharge cycle batteries. They have longer life cycles than the flooded lead acid battery [36]. However, AGM batteries are not suitable for high temperature operation.

4.4. Inverter

Inverter is an electrical circuit that converts DC power to AC power. Most of the electrical equipment is designed for line AC (240 V_{rms} and 50 Hz) and therefore an inverter is required to convert the DC form battery bank to AC. There are various topologies of inverters and the choice depends on the type of application and cost. Fig. 7 shows a basic topology for an inverter.

On the basis of output waveform, inverters can be broadly classified as:

- Square wave inverter
- Modified sine wave inverter
- Pure sine wave inverter

Square wave inverters are simplest of inverters and are least efficient. They have a large percentage of harmonic content that causes electromagnetic interference and losses in inductive components. Modified sine wave inverters are better in both efficiency and performance. Pure sine wave inverters have the least harmonic content, however they are very expensive compared to other two types and are primarily used for grid-tied systems and sophisticated applications such computer power supplies.

Fig. 8 shows a typical inverer configuration based on a standard H-Bridge. In this toplogy, switches S1 and S4 are turned ON simultaneously keeping the other switches OFF. When S1 and S4 are turned on, a positive voltage appears across the output. Similarlty, when S2 and S3 are ON (keeping S1 and S4 OFF), a negative

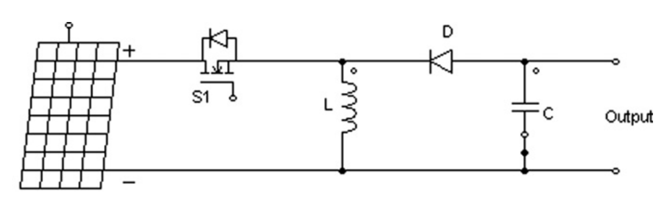

Fig. 7. Buck-Boost converter for a PV system.

voltage appears across the input of the transformer. The transformer then steps up this low voltage to 240 V_{rms} at the output which could be utilized by various AC-applications. Based on this basic principle, an inverter connverts a DC voltage into AC.

5. Current state of affairs for PV in Pakistan

In Pakistan, the situation for induction of solar energy into the energy mix is unfortunately not a very heartening one. Political inclination towards conventional fuels and rental power is severely affecting the overall growth of the renewable energy sector. In these circumstances, the role of private sector in PV is crucial in the overall energy mix of the country. The indigenous production of Solar PV related components is limited in Pakistan. Numerous organizations in private sector are offering stand-alone PV systems for low output power levels. However, the basic design methodology is not optimum as it lacks incorporation of various important parameters which are critical in the overall performance of a PV system. There is a severe lack of technical know-how and trained personnel in the industry which is echoed by almost all the studies on PV for Pakistan.

In the early 1980s, eighteen PV stations were set up by the government in different parts of the country for village electrification, with an installed capacity of nearly 440 kW [11]. Due to lack of technical knowledge about operation and maintenance requirements, these systems were no longer in operation after a few years of their deployment. Unfortunately, the situation has only marginally improved over the past two decades. In 2001, Pakistan Council for Renewable Energy Technologies (PCRET) started ensuring development and sustainability of solar and other renewable energy projects in the country. Alternate Energy Development Board (AEDB) joined such efforts in 2003 but unfortunately both the governmental organizations are weak in financial and technical manpower resources to imagine any breakthrough in the near future [1].

In National Renewable Energy Policy (NREP) 2002, besides other policy matters, following targets were set for Pakistan [16];

1. Renewable energy resources will acquire 3% share in primary commercial energy supply by 2010.
2. Every year 2% of the annual development budget will be allocated for the development of renewable technologies in the country.
3. All localities anticipated to be connected with national grid in the next 30 years are to be reserved for renewable energy sources.

We are in no way close to achieving these targets for Pakistan. Renewable (other than hydroelectric) is virtually negligible of the total energy mix in 2012 (Fig. 1). The projections for 2030 are

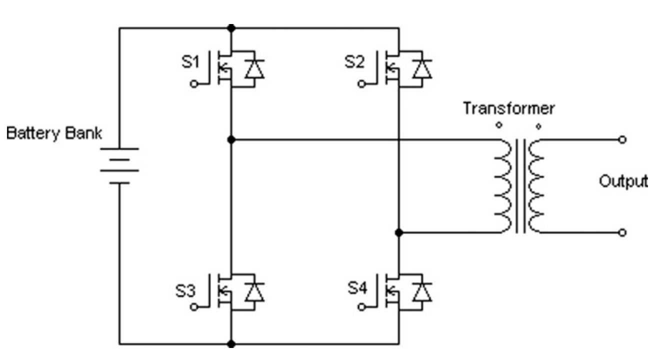

Fig. 8. Typical full-bridge inverter configration.

highly optimistic unless there is a large influx of investment from industrial sector and smaller distributed units from domestic consumers.

Solar PV based solutions exist and are being explored at different levels from individuals to organizations to specific industrial sectors to various government departments, that are involved in areas related to energy and energy systems. Lack of a coherent strategy at the national level has resulted in introduction of incomplete solutions that are at best sub-optimal. Many organizations have entered the market with little understanding of both the unique nature of the problem and the specific strengths of the solutions being proposed to confirm the right technological solution for the problem being addressed. This has further aggravated the situation where wrong and/or sub-optimal introduction of a new technology has created a barrier on further investment. There needs to be a much more effective coordination among government institutions, Private Power and Infrastructure Board (PPIB) and other stakeholders to address this energy crisis.

People in Pakistan are generally skeptical about PV. Due to sub-optimal designs, the energy output of the overall system is generally much less than the required value. This is due to lack of proper planning and insufficient knowledge of important parameters. This raises doubts in the minds of the end users about overall applicability of PV systems and restricts new investment in such systems. Therefore, the social acceptability of PV in Pakistan is very low compared to other regional countries such as China, India, Bangladesh and Malaysia where PV is starting to build its roots. For instance, India has added around 1100 MW of renewable energy [37], whereas china had 3.2 GW of installed renewable capacity as of 2011 [38].

In our study, we conducted a survey of several well-known companies dealing in PV in Pakistan and we have identified several problems in basic design mechanism for almost all organizations.

1. Almost all of the companies are offering solar panels which are based on crystalline silicon (c-Si). c-Si based cells have an inherent disadvantage because of a high negative temperature coefficient for output power. This means that the power output of a cell will decrease aggressively with increase in the ambient temperature. The temperature coefficient of c-Si is around (0.44–0.48)% per degree rise in temperature [39,40]. This means that the efficiency of the cells will decrease by around 0.46% of the rated with rise in 1 °C above 25 °C.
   Pakistan lies in a hot climatic zone and in summers the atmospheric temperatures may average around 45 °C [41]. This causes the enclosed cell temperature to easily rise above 80 °C. Therefore, the efficiency can be lowered by 25% of the rated at Standard Testing Conditions (STC). Thus, the system delivers far less power than it is designed at and raises serious doubts about the overall system reliability.
2. PWM based charge controllers have lower cost and therefore these are commonly used in PV applications in Pakistan. These charge controllers do not operate the solar panel at maximum power point and reduce the overall system efficiency.
3. Primarily, inverters used in Pakistan are square wave inverters. This is due to their easy construction and availability of low frequency components, including transformers. However, these are very inefficient, with efficiency lying around 40–50%. This results in following:
   - Due to higher order harmonics, power is lost in these inductive elements.
   - The inverter design does not cater for inductive load and results in higher device stresses, thus reducing its life.

4. The batteries currently being used are either flooded lead acid batteries or the sealed lead acid AGM batteries. Flooded lead acid batteries are not designed for deep-discharges. PV-systems usually require deep discharge cycles on a cloudy day or at nights. This results in poor performance of flooded batteries and rarely last for over a year. A relatively better implementation is through AGM batteries which also have certain issues. AGM batteries are quite sensitive to high temperature and in a country with hot climatic conditions, these batteries are not very suitable. The life of the batteries substantially reduces if the operating temperatures reach above 45 °C. The use of such batteries in a PV system not only affects the overall efficiency of the system but may potentially cause a battery failure resulting in system failures:

These are some of the most obvious flaws which we encountered in our research on PV systems in Pakistan. Improper choices result in un-optimized systems and affect the overall system reliability.

6. Proposed design improvements:

1) The temperature coefficient for thin film solar cells is around -0.22% per degree rise in temperature [40] which is roughly half of the c-Si based cells. This implies that the performance degradation of thin film panels (CdTe, CIGS and amorphous-Si) would roughly be half to that of c-Si based panels. Therefore, thin film based solar panels are most optimum for harsh climatic conditions of Pakistan especially in Southern Punjab, Baluchistan and Sind. Generally, it is not convenient to directly measure the cell temperature enclosed in a panel. Therefore, in order to predict the temperature of a solar cell, following quantities are to be ascertained:

   - Air temperature (T_{Air})
   - Insolation level (S in mW/m^2)
   - T_{Noc} (Normal Operating point temperature)

   T_{Air} and S can easily be measured through thermocouple and an irradiance meter while T_{Noc} is provided by the manufacturer of the solar panels.

   Knowing these three, the cell temperature can be calculated as [42]:

$$T_{Cell} = T_{Air} + \frac{T_{NOC} - 20}{80} \times S \tag{3}$$

   Knowing the cell temperature, the degradation in output power can be calculated and for proper sizing of the PV system, the degradation of power output with temperature should be taken into account.

2) MPPT based charge controllers should be used to maximize the system efficiency as these can extract 30% more power out of a solar panel.
3) For warmer regions of the country, Gel-based lead-acid batteries should be preferred over AGM and others for their better performance at higher temperatures.
4) Inverters utilized should be modified sine wave inverters for the off-grid/standalone systems as they do not produce high harmonic content to the system. For sophisticated applications and grid-tied systems, pure sine wave inverters should be employed.
5) Stand-alone system design should not be based on the average insolation per day in a year. For instance, the average variation insolation in Pakistan is around 5.2 peak sun hours/day, however the average for various months is considerably different as shown in Fig. 9 [43]. Therefore, modeling should be performed with respect to the critical requirement and the overall input insolation for typical low insolation months. Fig. 9 shows the monthly change in solar insolation for the major cities. Using this data, minimum and maximum available energy can be calculated and the design can be modified accordingly. A generic average insolation value of 5.2 peak sun hours/day will lead to lower output energy in the winter months.

7. Conclusions

Energy plays an integral role in socio-economic uplift of a country. A gradual shift is observed globally, in primary energy resources, from conventional to renewable sources. For Pakistan, we have identified technological inadequacies as one of the prime deterrents for PV growth. This adds to the lack of social acceptability and other barriers for a widespread growth of PV in the country despite its vast potential. Pakistan, being a developing nation, should optimally utilize all the available resources. In the wake of severe electricity shortages, it is high time for the country to tap into the abundant available PV to meet its needs. From the scope of the study, we have identified following technological improvement which can be highly beneficial for solar PV utilization in the country,

- The use of thin-film based solar PV generators in warmer regions of the country.
- The use of sealed Lead-acid deep-cycle batteries in place of usual automotive or AGM batteries.
- The use of MPPT based charge controllers for maximum power extraction.
- Finally, the use of high frequency inverters instead of square-wave ones which are currently widespread in the market.

8. The way forward

Pakistan is a developing country and a reliable access to energy and electricity is a requisite for its growth and sustainability. We believe it is imperative that solar PV should be a major part in the energy mix of the country in the next few decades. In the light of this study we have addressed some important constraints to widespread utilization of solar PV technologies that have been documented by Khan et al. [16];

1. High initial cost of PV system

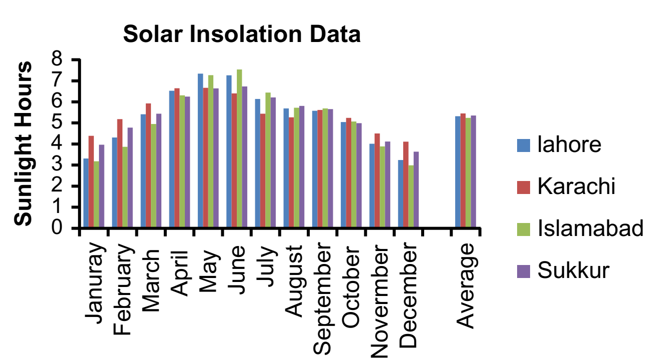

Fig. 9. Average solar insolation for major cities of Pakistan (adapted from NREL data [23]).

2. Inadequate renewable energy policy (in fact the government has not properly realized the need of renewable energy technology)
3. Unawareness in local communities
4. Inadequate availability of technical knowledge.

These issues can be largely addressed by the roadmap provided by this work which outlines the suitable technologies as well as insight about the state of the PV market. The roadmap is summarized as follows

1. The cost of PV has generally decreased considerable over the past few years and we believe sub-optimal designs also add to the high initial cost. Detailed analysis on the requirements and tracking of maximum power point along with analysis on the geographical profile can reduce the cost and enhance the reliability of the system.
2. The government should advocate the import of low-cost thin film based solar panels for Pakistan due to adverse weather conditions. In addition, no import duty should be charged on high performance invertors and other high efficiency components for better reliability. At the same time, large funding should be sanctioned to universities and research institutes to develop indigenous high efficiency power electronics components for these PV systems. Indigenization of these technologies can reduce the initial costs to a large extent.
3. In addition to creating general awareness about PV in local communities, we need to impart faith in PV with improved reliability of systems. This can only be achieved through optimum selection of components and better modeling which can address some of the social barriers in widespread deployment of PV.

In this study, we found out that the technological awareness of PV systems in Pakistan is limited at best. This is also corroborated by almost all of the studies on PV in Pakistan. For this purpose, we have set basic guidelines for most optimum components in the modeling of a PV system for generic applications. Moreover, we propose that the universities should take a lead in offering detailed courses about PV planning and development of systems which could cater for the energy needs of the country. Here, we would like to mention that School of Science and Engineering, Lahore University of Management Sciences (LUMS) has offered a course in Renewable Energy Systems to give students an exposure to the basics of PV modeling and analysis, prototyping and development and cost benefit analysis of these systems. All other the major universities such as National University of Science and Technology, University of Engineering and Technology and Ghulam Ishaq Khan Institute of Engineering Sciences and Technology should follow suit and offer such courses which can have direct implications on the PV market in the country by reducing this severe unawareness on the technological front.

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